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CONTENTS

Problems of the Technique of Steel Casting with Electro-Slag Feeding 1

Air Hardening Bonds for Molding Sands 5

Melting Practice to Produce Extra Low-Sulfur Carbon Steel 11

Organic Bonding of Steel Foundry Sands 12

Abstracts of Fundamental Papers on Steel Casting Research 15

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PROBLEMS OF THE TECHNIQUE OF STEEL CASTING WITH ELECTRO-SLAG FEEDING

by

G. S. Tyagun-Belous and D. A. Dudko*

A technique for producing steel castings by electro-slag feeding without using risers is described. The castings produced are shown to be physically uniform and chemically homogeneous.

A method of producing castings or ingots without risers, using electro-slag feeding, has been developed at the Ukraine S.S.R. Academy of Sciences Arc Welding Institute; this method was described in Reference 1.

The present article examines certain problems in the techniques used in this process; it gives results of research into the quality of steel castings weighing about one ton.

The direction of solidification can be controlled if the temperature of the upper part of the casting is higher than that of the remainder, throughout the process. This requirement is satisfied during electro-slag feeding by the fact that there is a bath of slag covering the upper part of the casting surface, which transfers heat to it. The electro-slag process is stable over a wide range of changes in welding conditions. For example, currents of 150-5000 amps, voltages of 20-60 volts, and electrodes of 0.10-4.0 inches or more diameter can be used.

Electro-slag feeding conditions cannot be arbitrary, since the current and voltage are selected with relation to electrode diameter, and this in turn is decided by the casting weight. As a rule, casting gate rods 1.6-2.0 inches in diameter are used as the electrodes for electro-slag feeding ingots weighing up to five tons. The ranges of currents and voltages which can be used are therefore quite narrow—1000-1600 amps and 45-58 volts. It has been established that at 1200 amps and 50 volts the rate at which a 1.57 inch diameter electrode melts is 1.1 to 1.2 pounds/minute. The additional metal required for feeding a one-ton casting is melted in 25-30 minutes and the casting solidifies in a sand mold in about 50-60 minutes. Therefore if feeding is carried out continuously, using the above conditions, until the casting has completely solidified, an unnecessary amount of metal is melted. If feeding is stopped before solidification is complete, shrinkage cavities form inside the casting or at its surface while the remaining metal pool is crystallizing.

In view of this, when producing 1600 to 2400-pound castings, it is advisable to use an intermittent electro-slag process, with various sets of conditions for the different stages. It should be noted that when using staged conditions two or three castings can be fed simultaneously; this is an advantage of the process.

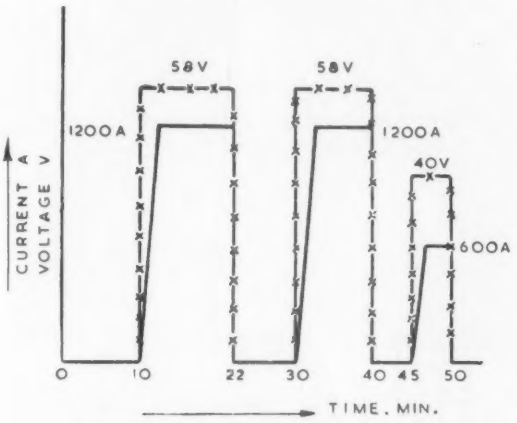

Figure 1—Conditions for one-ton casting.

As an example, Figure 1 illustrates the conditions used for feeding a casting weighing about one ton. The illustration shows that feeding is in three stages:

1) The initial stage—8-10 minutes after pouring is complete; duration 10-12 minutes.

2) The intermediate stage—starting 6-10 minutes after the end of the initial stage; duration 10-12 minutes. The conditions are about the same for the first two stages.

3) The final stage—starting 5-7 minutes after the end of the intermediate stage; duration 5-6 minutes. In this stage current and voltage are lower than in the first two stages.

The time interval between completion of pouring and the start of feeding is necessary for the following reasons: at the start of cooling, the particles of molten metal subside uniformly over the whole cross section of the casting. There is therefore no need to feed or introduce additional heat immediately after pouring. In addition, it is very difficult to initiate the electro-slag process on a molten metal surface, since the electrically conductive flux used for the purpose[2] may sink into the molten metal.

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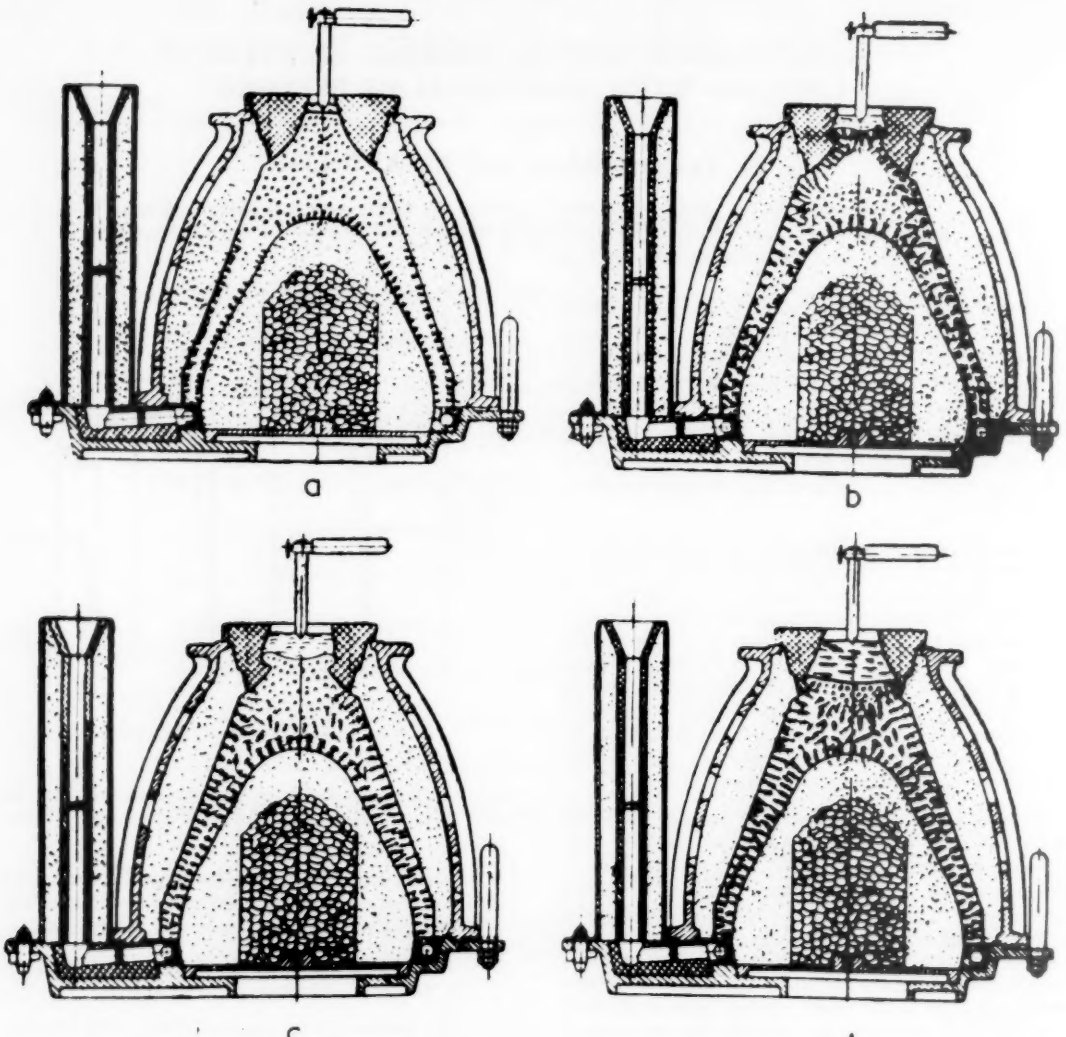


Figure 2—Diagram of electro-slag feeding: (a) start of feeding process; (b) addition of slag bath; (c) formation of metal bath; (d) end of feeding process.

During solidification, metal particles at the thermal axis sink to a much greater depth than those at the wall surfaces. The process is accompanied by the formation of a shrinkage cavity; it is at this moment that the casting must be fed.

To initiate the electro-slag process, a small amount of electrically conductive flux is poured onto the metal crust after it has formed, the electrode then being lowered into the flux (see Figure 2a). When the current is switched on, the electrically conductive flux is heated, and melts. At this moment the flux beneath which feeding takes place is poured in, and the 3 to 4¾-inch deep slag bath is formed (see Figure 2b).

The metal crust then melts, and forms a common metal bath together with the electrode metal (see Figure 2c); this is used up on filling cavities as they form. This bath is periodically supplemented by electrode metal (see Figure 2d). The number and duration of the breaks in feeding depends on the rate at which the metal bath solidifies. The breaks must amount to about 40 to 50 percent of the total time covered by feeding.

The necessity for ensuring process stability and the required amount of electrode metal should not be the only basis on which electro-slag feeding conditions are selected. The shape and dimensions (width and depth) of the metal bath are also most important.

Research and industrial experience have proven that the best conditions for obtaining chemically homogeneous castings are where the metal bath dimensions are maximum.

The explanation of this is as follows. During crystallization the metal bath, being the most heated part of a casting, is enriched with sulfur, phosphorus and carbon. Owing to metallurgical reactions between metal bath and parent metal, a considerable proportion of the sulfur transfers to the slag bath. Dilution of the metal bath by pure electrode metal (the latter being purified by the slag bath) plays a considerable part in making the metal bath chemical composition consistent; so also, of course, does the good metal pool stirring caused by convection currents and pinch effect.

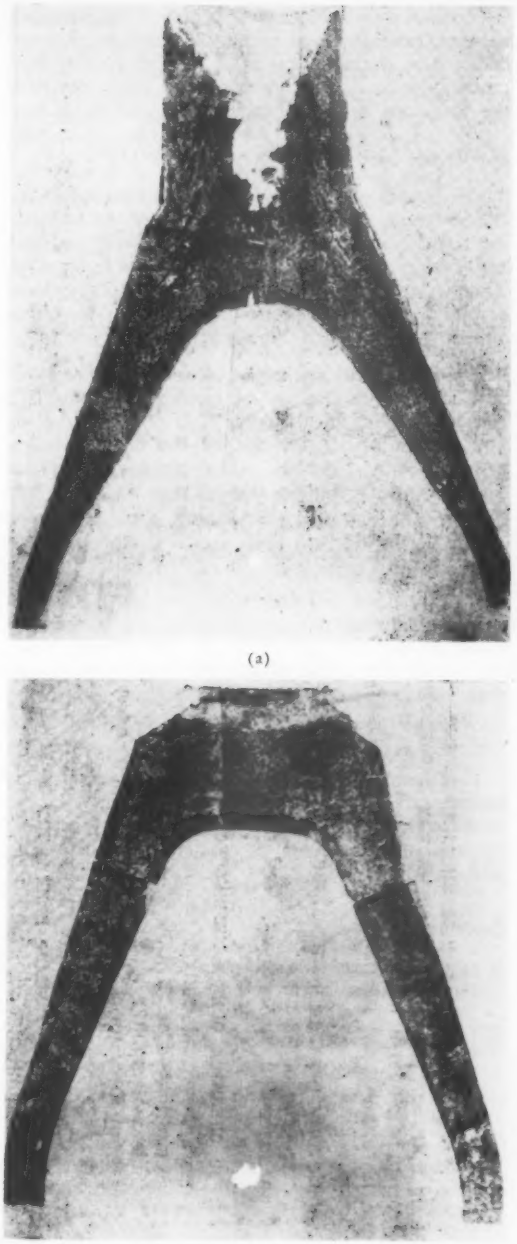
Owing to this, the upper parts of castings contain no very apparent segregation at or outside their axes. The segregates in the metal pool are uniformly distributed in the form of spots. The larger the metal bath and the longer the duration of feeding, the more segregates transfer to it; consequently the casting itself becomes chemically more homogeneous

Metal bath depth is directly proportional to the current (electrode feed rate). Metal bath width depends on the voltage and the free slag bath surface. Metal bath width increases with increase in the voltage.

It should be noted that a large metal bath is only necessary during feeding, and that its size should be reduced as much as possible by the end of the process. The smaller the bath the less the likelihood that the various types of unsoundness will form. This is achieved by greatly reducing the current, while keeping the voltage sufficiently high.

Thus physical uniformity and maximum reduction of casting chemical heterogeneity are the optimum feeding condition criteria.

Eighteen castings were investigated in order to assess the quality of castings produced with electro-slag feeding. Sulfur prints of longitudinal axial specimens from identical articles cast by the conventional technique and with electro-slag feeding are compared in Figure 3. A wide open shrinkage cavity, stretching the whole depth of the riser, can be seen in the first specimen (Figure 3a), and the casting metal is contaminated by segregations (the large spots). There is a clearly visible V-shaped extra-axial segregation region stretching from the riser 11 inches down into the body of the casting. There is also a well-developed segregation region at the bottom of the shrinkage cavity. The metal in the second specimen (Figure 3b) can be seen to be sound across its whole section. It contains no cavities or porosity, and there is no V-shaped or inverted V-shaped segregation. The segregates at the top of the casting are in the form of small spots.



(a)

(b)

Figure 3—Sulfur prints of longitudinal axial specimens: (a) cast by conventional technique; (b) cast with electro-slag feeding.

Casting chemical heterogeneity was investigated by analyzing the metal at various points. The chemical analysis results clearly showed that electro-slag feeding ensures satisfactory chemical homogeneity. The chemical composition discrepancies at the different points did not exceed ±10 percent.

Figure 4 shows the microstructure at the boundary between casting parent metal and crystallized metal bath. The casting metal is of pearlitic-ferritic fine-grained equiaxed structure. There is grain growth at the boundary between parent metal and metal bath caused by overheating, which has also caused the appearance here of acicular structures.

The figures given below show that, in spite of the coarser grain, the ductility properties of the metal in the upper casting zone, rather than being reduced, are considerably higher than those of the lower zone. This is evidently due to the more homogeneous chemical composition of metal which has been affected by the electro-slag feeding.

The mechanical properties of test pieces removed from certain test castings are given in Table I. It is clear from this table that the yield points at the top and bottom of articles cast by the new technique are practically identical. The tensile strength of lower zones is slightly higher than in the upper zones.

The elongation and reduction in area of metal from the upper casting zone are considerably greater, in every case, than the figures for the lower zone. It should be pointed out that, for parts cast in the same metal by the old technique, i.e., with feeder heads, the elongation is 40-50 percent less in the upper than in the lower zone. Consequently electro-slag feeding can improve the mechanical properties of cast steel.

Eliminating feeder heads and using casting gates as electrodes enables the output of sound metal to be increased by 18-20 percent. Table II contains a computation of the economic efficiency of electro-slag feeding when used for two steel castings.

Conclusions

1. Steel castings can be produced without using conventional risers by electro-slag feeding.

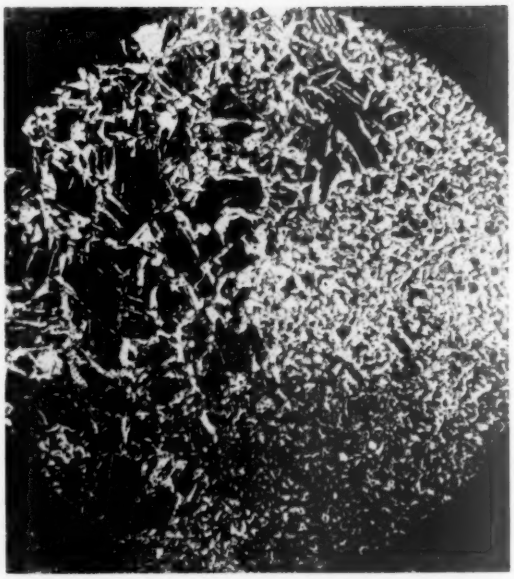


Figure 4—Microstructure at boundary between parent metal and metal bath (X100).

TABLE I—Casting Mechanical Properties

Casting	Test Pieces Removed From	Tensile Str., 1000 psi	Yield Str., 1000 psi	Elongation percent	Reduction in Area percent
1	top	64.5	50.1	11.6	24.0
	bottom	70.5	49.9	10.0	12.7
2	top	78.4	55.0	18.1	25.7
	bottom	70.4	50.6	11.8	17.7
3	top	73.6	49.6	20.2	25.0
	bottom	78.6	53.3	13.3	20.8
4	top	65.0	52.7	16.0	21.6
	bottom	73.0	51.2	9.0	17.1
5	top	69.8	45.4	20.3	32.0
	bottom	71.0	48.3	17.4	27.6

TABLE II—Economic Efficiency of Electro-Slag Feeding of Castings

Expenditure Items	CASTING A				CASTING B			
	Conventional Risering		New Technique		Conventional Risering		New Technique	
	Pounds	Percent	Pounds	Percent	Pounds	Percent	Pounds	Percent
Rough weight of casting	2295	57.4	2295	75.5	1100	54.5	1100	74.7
Feeder head and gates	810	19.6	44	1.5	454	22.5	33	2.3
Scrap	402	10.0	304	10.0	202	10.0	148	10.0
Spatter, mechanical losses, samples	521	13.0	395	13.0	260	13.0	190	13.0
Total metal	4028	100.0	3038	100.0	2016	100.0	1471	100.0
Metal economy per casting	.....	.....	990	18.1	.....	.....	545	20.2

2. Feeding conditions consisting of three stages with intervals of 8-10 minutes between them, are optimum for castings weighing up to 2400 pounds.

3. The electro-slag feeding of castings improves cast metal quality by eliminating chemical heterogeneity, and the output of sound metal is 18-20 percent higher.

References

1. G. S. Belous and D. A. Dudko, "A New Method of Producing Shaped Castings and Ingots Without Feeder Heads, by Adding Electro-Slag Metal." *Avtomatichskaya Svarka,* 1958, No. 8.

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AIR HARDENING BONDS FOR MOLDING SANDS

by

J. M. Middleton and F. Bownes*

The use of a binder in molding sands that will allow the mold to harden or "set" while standing in air offers certain advantages to the steel foundryman. The most important of these is the elimination of drying with the consequent savings in fuel and mold handling costs. Also, the replacement of green sand molding by an air hardening molding process should improve the quality of the castings, giving better dimensional accuracy, and greater freedom from sand inclusions with an accompanying improvement in machinability of the castings.

Air hardening bonds have been employed in foundries for a number of years, the most common one being Portland cement as used in the Randupson process. Sands bonded with sodium silicate and combinations of sodium silicate with sodium silico fluoride will air set to some extent, and it has been suggested that certain metallic phosphate solutions, e.g., aluminum ortho-phosphate, will give air setting properties when mixed with certain combinations of sands. All these binders, however, are inorganic and suffer from the disadvantage of having poor breakdown properties after casting. Also, air hardening of the bond may be slow, which necessitates long periods of waiting before the molds can be poured.

Air setting organic binders based on natural drying oils have been available for some time, but the original oils of this type were used exclusively as core binders. If clay is added to the sands bonded with such oils to provide the green strength necessary for molding purposes, the air setting properties could be adversely affected. More recently, several new organic binders have been developed that are suitable for either core or mold purposes, since they are effective when a certain amount of clay is present.

This paper describes work that compares the bonding properties of typical air setting oils for molds, i.e., the green strength properties in conjunction with clay and natural bonded sand additions, the rate of build up in strength on air drying, and the strength after baking. An indication is also given of the bench life of the mixes and the amounts of gas evolved from the binders during breakdown. The application of the binders in the foundry and also the advantages and disadvantages connected with their use are discussed.

* The authors are, respectively, Head of and Senior Investigator in the Molding Materials Section, B.S.C.R.A.

Air Hardening Oil Binders

A number of air setting, clay tolerant oils, all proprietary, have been examined, but for the purpose of this paper three typical oils have been selected. These are:

Oil A Linoplast (F. Raschig, Ludwigshafen)—A linseed oil alkyd containing driers.

Oil B Cataset 300G (Catalin Ltd., Waltham Abbey, Essex)—Probably of similar basic composition to Oil A.

Oil C Heavy Corovit (Fordath Engineering Co. Ltd., West Bromwich)—Possibly a mixture of drying oils combined with driers.

No exact details of the composition of the oils are available except in the case of Oil A which, according to B. P. Application No. 803,397, is probably a blend of linseed oil and of a synthetic resin, such as alkyd resin, with driers (metallic salts, e.g., lead or cobalt naphthenate). The other oils may be of similar type or may consist of combinations of drying oils only (linseed, tung, perilla, oiticica oils) together with driers.

It is known that the unsaturated fatty acids in an oil such as linseed must take up oxygen before they become capable of forming hard films by polymerization. This oxidation process may be very slow at room temperatures and heat is usually applied to increase the speed of oxidation and subsequent bonding of the oil. If, however, the oil is previously modified by partially oxidizing it by heating or blowing with air, it then becomes possible for the oil to harden at room temperatures in the presence of

suitable driers. Furthermore, it appears that if the proper choice of driers is made and suitable blends of drying oils or drying oils and synthetic resins are used, the oils have the unique property of developing good green strength when suitable clays are present, while retaining their air hardening and baked strength properties.

A controlled increase in the speed of air setting of the binders is achieved by the addition of small amounts (about 0.1 percent) of a powered oxidizing agent or "accelerator", such as peroxide or perborate salts, organic peroxides or calcium hypochlorite, etc. Reduction of the hardening time in this way shortens the storage or bench life of the mixes correspondingly.

Bonding Properties

The green and dry compressive strength tests were performed on standard 3 ram A.F.S. test pieces and the baked tests on 3 ram tensile test pieces. The base sand used throughout the tests was Chelford ordinary silica and the air set oil addition was kept constant at 3 percent. Sodium perborate was used as the accelerator, the addition being 0.1 percent (3 percent of the oil weight). The mixes were prepared in the laboratory end-runner mill with a mixing time of 5 minutes.

(a) *Properties of Straight Oil Mixes*—The air setting properties of the mixes were assessed by determining the strengths of specimens which had been allowed to stand in the laboratory for various times up to 48 hours after making. Straight 3 percent oil mixes with and without accelerator were tested and the results are shown in Table I. As it was recommended that dry sand be used for this type of mix, the effects of using moist sand were checked and the results are included in the table.

The addition of moisture to the mixes containing Oil A and Oil B hastens slightly the onset of hardening (set-up time), but has little effect on the strength values achieved. With Oil C, however, the presence of moisture delays the onset of hardening appreciably.

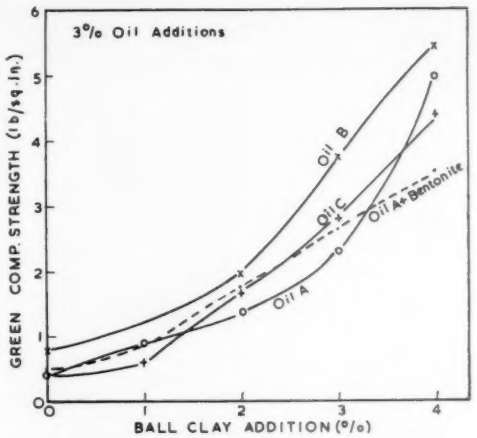

Figure 1—Effect of clay additions on the green strengths of the oil mixes.

Accelerator additions to the oil sand mixes reduce the period before hardening commences to about ½ to 1 hour and give appreciably greater strengths in all cases. All the straight oil mixes have green strength values between 0.4 and 1.0 lb/sq. in.

(b) *Effect of Clay Additions*—One of the important properties of these binders is their ability to give green strength with clay bonded sands, while retaining their air setting properties. Figure 1, which shows the effect of various ball clay and bentonite additions on the green compression strengths of the oil mixes, indicates that it is possible to attain the reasonable green strength value of approximately 3 lb/sq. in. by additions of 3 percent clay.

The effects of various clay additions on the air setting properties of Oil A and Oil B bonded sands are shown in Figure 2. It will be seen that increasing the amount of ball clay slows down the rate of hardening. Also, 3 percent bentonite additions give faster initial hardening rates for both oils, than the corresponding ball clay additions.

TABLE I—AIR SETTING PROPERTIES OF STRAIGHT OIL MIXES

Sand Mix (3% oil addition)	Green Strength lb/sq.in.	Start of Hardening hours	Air set Strength lb/sq.in. on standing for:		
			8 hr	24 hr	48 hr
Oil A	0.4	6	80	190	300
Oil A + 1.5% H_2O	0.5	5	60	165	275
Oil A + 0.1% Accl.	0.4	1	200	300	305 (30 hr)
Oil B	0.5	7	10	210	365
Oil B + 1.5% H_2O	0.5	6	15	220	370
Oil B + 0.1% Accl.	0.6	0.5	265	445	490 (30 hr)
Oil C	0.5	5	50	180	215
Oil C + 1.5% H_2O	0.7	9	5	100	235
Oil C + 0.1% Accl.	1.0	0.5	150	280	280 (30 hr)

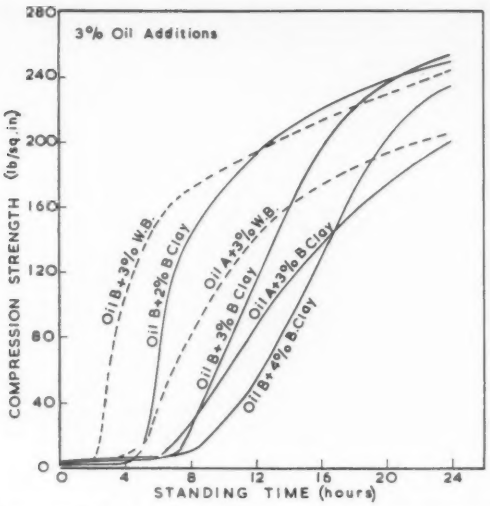

Figure 2—Effect of clay additions on the air setting properties of the oil mixes.

The results shown in Figures 1 and 2 indicated that a 3 percent addition of clay was probably the most suitable and all the synthetic sand mixes subsequently tested contained this quantity. The air hardening properties of the three oils with 3 percent ball clay are given in Table II.

It will be seen from Table II that, in the absence of accelerator and with 3 percent ball clay addition, a considerable time must elapse before hardening commences, but that an accelerator addition overcomes this deleterious effect of the clay and markedly shortens the set-up times. A moisture addition to the mixes adversely affects the green strength and usually lowers the rate of hardening of all the mixes.

(c) *Effect of Naturally Bonded Sand Additions*—As many foundries prefer to add a portion of natural sand to their mixes to give green strength, rather than work with solely synthetic mixes, the air setting properties of the oils were determined when proportions of Belgium Yellow and Rotten Rock sands were added to provide the clay (Table III).

Table III shows that naturally bonded sand additions are just as effective in giving green strength as the ball clay additions to the silica sand mixes. Additions of 20 percent Belgium Yellow or Rotten Rock sand, which make effective clay additions of 3.0 and 3.5 percent, respectively, give green strengths of 2.5-3.5 lb/sq. in. In all the mixes containing naturally bonded sands, an accelerator addition was necessary to give a rapid rate of hardening.

(d) *Effect on Air Hardening Rate of "Gassing" with Air*—It has been reported that Continental foundries are increasing the speeds of air setting of large, deep cores by passing compressed air or oxygen through them. In these instances, a proportion of a naturally bonded sand containing the mineral glauconite, e.g., Rosenthaler sand, is added to provide the clay bond. To test the possibilities of this technique, A.F.S. test pieces made in various sands bonded with Oil A have been gassed under standard conditions with oxygen. The sands tested included mixes containing 20 percent of Rotten Rock sand, 5, 10 and 20 percent of a British sand containing glauconite, and Chelford sand with and without a ball clay addition. Although there was always some increase in strength on gassing (the largest being from 2.5 lb/sq. in. to 10 lb/sq. in. with 15 minutes gassing), the strengths obtained were not comparable with the full air set values. Even when the cores were allowed to partly air set before gassing no great benefits were obtained.

(e) *Bench Life of Oil Sand Mixes*—A difficulty which may arise in the use of air setting binders is the relatively short storage or bench life of the mixes. In order to test this property, the "as milled" sand mixes containing each of the three oils (without accelerator) were allowed to stand, well spread out to allow easy access of air, for times up to 7 hours and test pieces were made at intervals during this time. The strengths obtained on the specimens after standing for a further 24 hours are shown in Figure 3.

TABLE II—AIR SETTING PROPERTIES OF BALL CLAY MIXES

Sand Mix (3% oil, 3% ball clay additions)	Green Strength lb/sq.in.	Start of Hardening hours	Air set Strength lb/sq.in. on standing for:		
			8 hr	24 hr	48 hr
Oil A	3.0	10	5	30	385
Oil A +0.1% Accl.	3.6	2	245	400	470
Oil A +0.1% Accl. + 1.5% H_2O	1.8	1	130	235	360
Oil B +0.1% Accl.	3.0	1	220	330	515
Oil B +0.1% Accl. + 1.5% H_2O	1.7	3	140	365	615
Oil C	2.5	—	5	5	10
Oil C +0.1% Accl.	3.8	1	70	240	300
Oil C +0.1% Accl. + 1.5% H_2O	1.8	2	90	205	290

The curves show that the oil mixes do not start to lose their bonding properties until 4 to 5 hours have elapsed. It must be remembered, however, that these results apply only to mixes without accelerator additions. An accelerator addition would considerably reduce the bench life, as would also over-milling, a warm sand, or a high air temperature in the foundry.

(f) *The Baked Properties of the Air Setting Binders*—While air hardening will develop a fairly high strength with these oils, to obtain their full bonding properties, the sand mixes must be baked. Figure 4 shows the tensile strengths, after baking at 390 degrees F for various times, of the three oils in 3 percent ball clay/Chelford mixes. All the mixes baked rapidly and achieved maximum strength within approximately one hour's baking. The tensile strength figures are high, similar in fact to a good oil bonded core sand and it would appear that the clay additions do not have a very deleterious effect on baked strength properties.

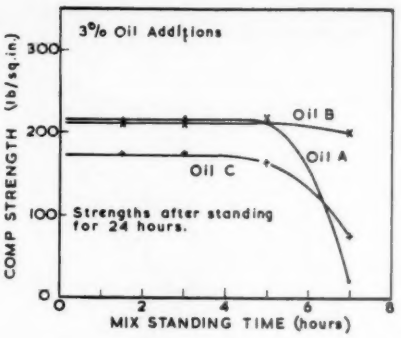

Figure 3—Bench life of the oil mixes.

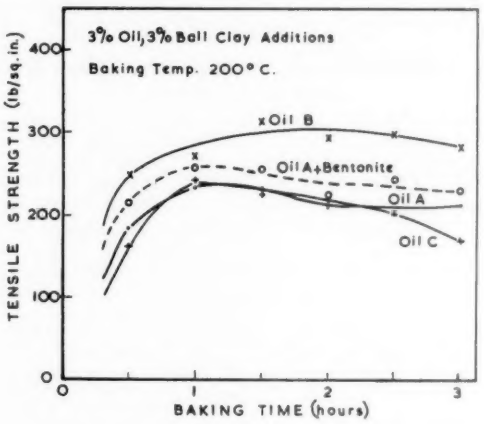

Figure 4—Baked tensile strengths of the oil mixes containing clay.

Rate of Gas Evolution

Certain foundrymen using these oils for mold bonding purposes have reported a tendency towards the occurrence of blowhole defects, particularly on the top parts of castings. Figure 5 shows a close up view of this defect in a 150-pound casting made at the Research Station. As the occurrence of the defect must be related to the rate and amount of gas evolved from the oil sand mix during the early stages of casting solidification, tests were carried out to compare the rate of gas evolution from the air set mixes with that from conventional oil sand mixes.

First, gas evolution rates were measured on samples of sand bonded with the oils when heated to 1590 degrees F in a laboratory furnace. The results

TABLE III—AIR SETTING PROPERTIES OF MIXES CONTAINING NATURALLY BONDED SAND

Sand Mix (3% oil addition)	Green Strength lb/sq.in.	Start of Hardening hours	Air set Strength lb/sq.in. on standing for:		
			8 hr	24 hr	48 hr
Oil A + 15% B.Y.	1.5	—	—	215	—
Oil A + 20% B.Y.	3.3	—	10	20	—
Oil A + 25% B.Y.	4.4	—	12	20	—
Oil B + 20% B.Y.	3.0	—	5	10	—
Oil B + 20% B.Y.+ 0.1% Accl.	3.1	0.5	180	275	—
Oil A +20% R.R.	2.5	7	35	280	335
Oil A +20% R.R. + 0.1% Accl.	2.4	1	235	290	330
Oil B +20% R.R.	3.4	9	5	245	425
Oil B +20% R.R. + 0.1% Accl.	3.2	1	240	360	475
Oil C +20% R.R.	2.5	8	10	220	300
Oil C +20% R.R. + 0.1% Accl.	2.7	1	180	260	310

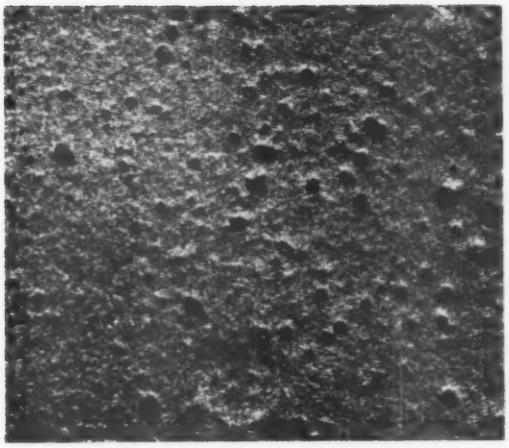

Figure 5—Blowhole defects in the cope of a 150-pound casting made in an air setting oil bonded mold (full size).

obtained with sands containing 2 percent of Oils A and B in the "air set" and baked conditions are shown in Figure 6. The result obtained on a sand bonded with 2 percent linseed oil and fully baked is also included for comparison. If will be seen that more gas is evolved, and at a faster initial rate, from the sands allowed to air set, than from those which have been fully baked. Also, a considerably greater volume of gas is evolved from Oil A than from the linseed oil mix. These results suggest that more trouble would be expected from blowhole defects with this oil, than from Oil B or from linseed oil mixes. They would also indicate less trouble when the oils are baked.

The laboratory method used for determining the gas evolution does not simulate the temperature conditions encountered during the pouring of the casting. Attempts were made, therefore, to measure the amount of gas evolved from an oil bonded sand, during and after pouring. The oil bonded core (4 inches x 1½ inches diameter), rammed into a steel tube and baked at 390 degrees F was inserted flush with the top face of a mold, and the gas generated on contact with the molten steel was measured by means of a flowmeter. Figures obtained for 2 percent oil additions, 15 seconds after completion of pouring, were 112 ml/min. for Oil A and 70 ml/min. for linseed oil.

An alternative method was to measure the gas pressure set up in the core near the metal mold interface. Initial results have shown that there is a pressure set up, almost instantaneously, of 10 cm of water for linseed oil. However, if the core protrudes 5/16 in. into the casting, the pressure increases to 87 cm of water for linseed oil. The results show that although on flat top faces of molds the pressures exerted might be low, they can become quite high at re-entrants in castings. They also confirm the trends

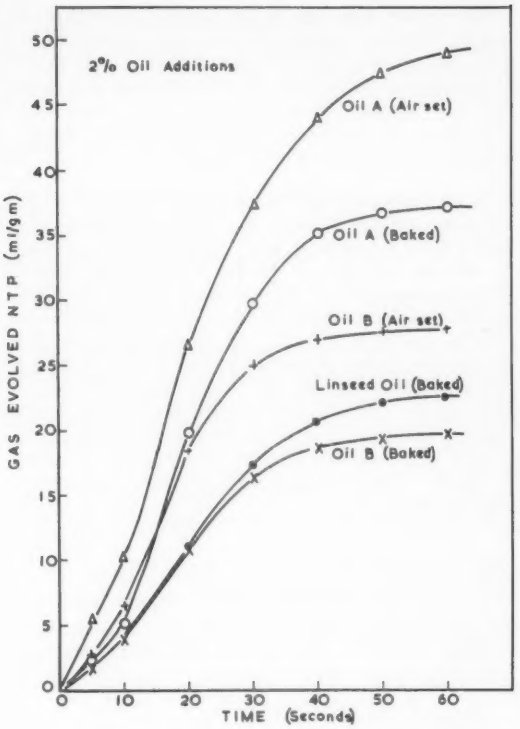

Figure 6—Gas evolved from baked and air set oil mixes.

of the laboratory tests, namely, that a greater amount of gas and higher gas pressures will result from the breakdown of certain of the "air set" oils than from normal oil binders, e.g., linseed oil. This should always be kept in mind when using these oils. If blowhole defects are to be avoided, foundrymen should endeavor to keep oil additions to a minimum, use as open a backing sand as possible and vent well, especially near re-entrants.

Foundry Application

Air setting oils are used in two ways for mold production: (1) as a binder in a facing mix, and (2) diluted with a suitable carrier vehicle, such as paraffin or isopropyl alcohol, and sprayed on to the mold surface.

Various silica or zircon base sands can be used for oil bonded facing mixes and a proportion of clay, either as pure clay or as present in naturally bonded sand, is added to give the required green strength properties. These clay additions are kept as low as possible, as clay has a deleterious effect on the flowability of the mix. With these mixes an accelerator addition (usually finely ground sodium perborate) is necessary to give a sufficiently high rate of air hardening.

The molds may be hand rammed or machine molded. Various methods of curing the molds are employed, such as air drying for times of up to 24 hours, light oven baking, electric pressure drying or infra-red heating. Certain foundrymen hold that, even after air hardening, a light application of heat is beneficial in stabilizing the bond.

Considerable savings in costs can be achieved by using the air setting oils and sprays, although the results are not usually as good as those obtained with the oil bonded mixes. At one steel foundry where the sand practice is based on naturally bonded sand, all the molds are sprayed, and this is claimed to prevent scabbing defects. It is also possible that the use of sprays might overcome any deleterious effects of using inferior molding sands. Spraying is particularly useful in machine molding work, since it eliminates the use of a separate facing mix. The sprayed molds may be allowed to air set or are dried by means of radiant heaters, torching, or ovens for heavy work.

TABLE IV—Fluidity Spiral Tests (0.30 Percent Carbon Steel)

Mold	Spiral Length (in.)
Cast at 2870° F.	
Sprayed Oil A	17
Sprayed Oil B	18
Green Sand	19
Cast 2800°F.	
3% Oil A, 3% Ball Clay	13.0
3% Oil B, 3% Ball Clay	9.5
Inflammable Spray	9.0
Green Sand	10.5

In general, good peel is obtained with castings made in air set oil bonded molds and in some cases surface finish is reported to be excellent. The mixes are being used for castings of up to about 10 tons in weight, but for the larger section castings a zircon wash has to be applied to prevent metal penetration. The binders are also said to be particularly useful in the production of high alloy steel castings, giving an improvement in surface quality with austenitic manganese steel and a reduction or elimination of lapping defects with stainless steels. To determine whether or not molds containing or sprayed with these oil binders allowed the metal to flow more easily over their surfaces, fluidity spiral tests were made (Table IV).

It will be seen that the use of oil sand facing or oil sprays has had little effect on the length of the spirals obtained. It would appear, therefore, that the presence of these binders on the surface of the mold does now allow this type of steel to flow more easily. However, one thing that has been noted, which is not shown by the fluidity test, is that castings poured in air set molds appear to be sharper and better defined than similar castings poured in green sand molds.

Discussion

It has been shown that it is possible with the oil binders described to obtain a reasonable degree of green strength in the mixes and still retain adequate air setting and good baked strength properties. Either a kaolinite or bentonite clay may be added to provide the green strength, and the typical properties which would be obtained with 3 percent clay, 3 percent oil and 0.1 percent accelerator additions are: green strength 3 lb/sq. in., 24 hour air set compressive strength 330 lb/sq. in., and baked tensile strength 310 lb/sq. in. An average time for hardening to commence for this type of mix is 2 hours after milling. Instead of a pure clay addition, a proportion, approximately 20 percent, of naturally bonded sand, e.g., a Rotten Rock, may be added to give the same effect. The base sand employed should be dry, as it has been found that small amounts (1.5 percent) of moisture lower the green strength and the rate of air hardening. The bench lives of the mixes under fairly severe conditions were found to be approximately 5 hours, but these would be considerably reduced in the presence of an accelerator.

A greater amount of gas may be evolved from these binders than from similar amounts of conventional oils, e.g., linseed oil, and a mix which has been air hardened will evolve more gas than one which has been fully baked. This might account for certain blowhole defects which have sometimes been encountered when using these binders.

The main advantages claimed when using the binders as mold facings are the elimination of baking with the consequent savings in fuel and mold handling costs; good surface finish and dimensional accuracy, which reduce machining allowances, and a possible reduction in sand inclusions with improvement in machinability. Beneficial effects are also obtained by using air setting sprays on naturally bonded and unit sand molds.

Disadvantages are the high cost of the binders; a possible tendency for variation in properties of the binders from batch to batch; necessity for a supply of cold, dry sand and close control over mix additions and milling procedures; sensitivity to variations in air temperature and humidity; possibility of sand wastage because of the short storage life of mixes, and a greater risk of blowhole defects.

Air setting oil binders should find increasing application in the steel foundry, particularly if their costs could be reduced. It must be pointed out, however, that the use of these materials necessitates a closer measure of control than with normal bonding materials and some initial difficulties may have to be overcome before satisfactory results are obtained.

MELTING PRACTICE TO PRODUCE EXTRA LOW-SULFUR CARBON STEEL

by

A. J. Kiesler*

The following is a summary of a paper presented at the 17th Annual Electric Furnace Conference held at Cleveland, Ohio, on December 2-4, 1959. The author describes his process for reducing the sulfur level of basic electric steel to 0.005 percent or lower.

In the process developed, the metal to be purified is melted down with conventional slagging components designed to enable effective removal of phosphorus and FeO. As soon as the FeO and phosphorus contents of the melt have been reduced to their predetermined levels, the slag is removed.

A second slag is prepared using two parts of lime, one part of graphite and one part of finely divided silicon. These materials are pre-mixed. An addition of 0.10 to 0.15 percent of aluminum pig to the heat may be made at this point to aid in the desulfurizing operation. This second slag is then worked into the heat by appropriate mixing operations so as to effect rapid and almost complete sulfur removal. This carbide slag is then carefully removed in order to prevent re-entry of sulfur or reversion of sulfur into the metal during subsequent processing.

As the final step of the process of purifying the steel, oxygen is blown into the metal so as to oxidize the carbon, manganese, silicon and aluminum. During this blowing operation, the metal is protected from sulfur-bearing materials and the sulfur content of the metal is thus maintained at the minimum established in the desulfurizing operation. Following this oxidation step, the metal is treated as required (manganese and silicon additions) and tapped and cast suitably in accordance with generally conventional practice.

The activity of the iron sulfide or calcium sulfide varies with the metal analysis. When the carbon and silicon are high, the sulfur has a greater tendency to leave the bath than when they are low. This can easily be seen in the desulfurization of cast iron in the ladle with calcium carbide. Better sulfur removal is achieved if it is done before oxidation, which is the basis of this process.

It has long been recognized that there is a need for some method or means by which the sulfur content of iron and steel can be rapidly and economically reduced to the region of 0.005 percent.

Sulfur reduction has traditionally required a basic lined furnace to maintain a slag of sufficient basicity to absorb and retain sulfur from the metal. The optimum ratio of sulfur in the slag to sulfur in the metal requires a highly basic slag very low in iron oxide, which can be accomplished best in a basic electric furnace after a prolonged reducing treatment. The longer heat time made necessary by the slag conditioning makes the removal of sulfur an added expense in steel making.

In the process developed it is possible to reduce sulfur to levels lower than 0.005 percent without a substantial increase in cost over the standard two-slag practice.

The conventional practice, in a two-slag basic electric steel heat, is well known: melt down, oxidize with oxygen or iron ore, block with silicon and manganese, remove the slag, add a reducing slag, tap and pour.

TABLE I—Log Sheet for Carbon Steel

Charge:	1400 pounds
Melt Down:	52 minutes (cold furnace)
Melt Chemistry:	C, 0.68; S, 0.026; P, 0.029; Mn, 0.60; Si, 0.16
Drain Slag:	5 minutes
Add New Slag:	16 lbs. lime, 12 lbs. graphite, 6 lbs. FeSi
Remove Slag:	12 minutes after adding
Inject Oxygen:	2 minutes
Alloy:	Mn and Si in furnace—aluminum in ladle
Tap:	Total time—1 hour 15 minutes—600 KWH

TABLE II—Chemical and Mechanical Properties

C	0.17%	Tensile Strength	60,000 psi
S	0.003%	Yield Strength	38,000 psi
P	0.019%	Reduction of Area	52.6%
Mn	0.56%	Elongation	37.0%
Si	0.26%	Charpy V-Notch at –40°F	38 ft-lb.

Table I is a condensed log sheet showing the pertinent steps in the process. It shows a removal of the carbide slag 12 minutes after adding but fails to point out that this slag is vigorously rabbled during this 12-minute interval. The total power consumption at 600 KWH is higher than normal; however, this is primarily due to an inexperienced melting crew. The author feels that this could be substantially lowered with an experienced crew.

* General Electric Company, Research Laboratory.

Table II shows the chemical and mechanical properties. For a steel this low in alloy content these mechanical properties are excellent. The type of inclusions present in the steel was also investigated. Type I and Type III sulfide inclusions were found. An extremely small amount of these inclusions was present.

The gas content of steel produced by this method is very low for perhaps two reasons: the first being the time interval between the end of the oxygen blow and the tap which is usually less than two minutes; the second reason being the ability to control the temperature with the oxygen and finishing the heat after the removal of the carbide slag without using power.

ORGANIC BONDING OF STEEL FOUNDRY SANDS

(Final Report on Research Project No. 45)

Studies on shell molding of cast steel have shown that the two-step phenol-formaldehyde resin can be successfully employed with silica sand to produce cores and molds. Urea-formaldehyde resins and one step phenol-formaldehyde resins also can be used to bond sand for steel castings, but they lack certain properties which the two-step resin possesses.

One of the chief disadvantages of resin binders is the enormous quantities of gas they release as the resin is dissociated by heat into hydrogen, methane, carbon dioxide, nitrogen and water vapor. The gas is released quickly, and if it occurs during the solidification of the skin of the steel casting, the gas released impairs the casting surface smoothness and may cause a lack of casting definition.

The Technical Research Committee realized that very little was known in the field of organic binders and therefore, the Committee undertook the research studies as a joint undertaking with Monsanto Chemical Company, Massachusetts Institute of Technology and the Steel Founders' Society of America because of Monsanto Chemical Company's knowledge of resins, plastics and other organic compounds that might act as binders suitable for steel foundry application. Monsanto was to formulate, produce and study the properties and behaviors of all potential organic bonds and Massachusetts Institute of Technology was to ascertain their effectiveness when bonding mold sands for the production of steel castings.

However, Monsanto Chemical only contributed 1 to 1½ days a month to the realization of the project and in 1959 the Technical Research Committee cancelled its contract with Monsanto Chemical Company, as no new organic binders had been sent to M.I.T. for 15 months.

The studies were limited to organic binders of the phenol-formaldehyde type for use only in producing shell molds. Melamine and urea-formaldehyde resins, alone and in combination, were found unsuitable for steel castings because of the excessive gassing at steel casting temperatures.

Various additives such as manganese dioxide, lead dioxide and ceris sulphate were ground into the better lump resins. Limited data indicated a lessening of surface carburization in casting thin walled stainless (304) in shell molds. Additives must be pure, as such impurities as clay, mica, and silica adversely affect their use.

Several approaches were made to the hypothesis that shell casting defects called "pocking" or excessive discontinuous "pitting" resulted from the rate of casting skin formation and the gas evolution rate of the resin binders. A systematic resin synthesis program was initiated to screen generic phenolics, modified phenolics, as well as other thermosetting binders.

The syntheses of resins were designed to produce:

1. low, slow evolution of gas per unit time.
2. high evolution of gas in a short time, followed by slow evolution of gas per unit time.
3. low evolution of gas in a short time, followed by high evolution of gas per unit time.
4. slow evolution of gas with "controlled" reducing or oxidizing atmosphere by the use of pyrolysis additives.

Experimental Resin Synthesis

A large number of phenolic resins were synthesized at Monsanto Chemical Company as possible binders to be used in the production of shell molds. Resins were synthesized with different catalysts in order to determine the effect of molecular weight distribution on gas evolution rate during casting; phenolics were blended with melamine and urea-formaldehyde resins to produce fast gassing and stability; and various thermoplastic modified phenolic resins were made to provide a "controlled atmosphere" gas at the mold-casting interface.

Several resins deemed suitable as a binder for making shell molds were sent to M. I. T. for test purposes. The binders evaluated by M. I. T. were as follows:

Resin A—A phenol-formaldehyde resin used as a standard.

Resin B—A phenol-formaldehyde binder from which certain gas forming materials were removed.

Resin C—A phenolic binder, highly modified with unrelated polymer.

Resin D—A phenolic binder, highly polymerized to eliminate low molecular weight materials.

Resin E—A phenolic binder, polymerized under the influence of a catalyst.

Resin F, G & H—Phenolic binders polymerized with very broad catalyst concentrations.

Resin I—A phenolic resin binder.

Resin J—A phenolic resin binder.

Resin K—A liquid resin for room temperature coating of sands.

Resin L—A powdered resin for coating sands.

Gas Evolution Rate of Resins . . . Measurement of gas evolution rates of the resins to be tested by M. I. T. was made in an atmosphere of nitrogen at 1600 degrees F. A 0.500 gram sample of the cured and ground resin was used to determine the gas evolution rate. The gas evolution rates for the various resins is shown in Figure 1. It was observed that seven of the resins had comparable rates and their rates are shown as a band. Three resins had distinct evolution rates.

Evaluation of the Potential Resin Binders . . . The studies by Monsanto were limited to organic binders for use only in shell molding. Studies were made on organic binders other than phenol-formaldehyde resins, but none were deemed suitable for steel molding sands.

The test shell mold design used to evaluate the various phenol-formaldehyde resin is shown in Figure 2. The shell molds were made by adding 5 percent

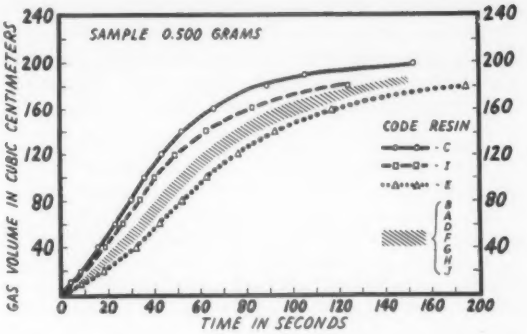

Figure 1—Gas volumes, in cc, evolved for various phenolic resin binders heated to 1600 degrees F.

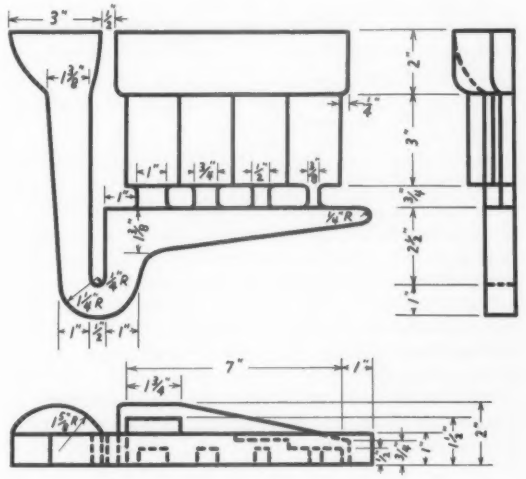

Figure 2—Test casting design.

TABLE I—SUMMARY OF TEST DATA FOR 5 PERCENT ADDITIONS OF PHENOLIC RESINS TO SILICA SAND

Resin Identification	Mold Density lb/cu. ft.	Average Mold Thickness in 64th in.	Time in sec. to Evolve 180 cc of gas*	Pouring Temp. Degrees F	Casting Rating in Relation to Standard
A	0.050	20.0	153.0	2875	Standard
B	0.046	20.0	151.5	2850	Inferior
C	0.047	21.5	88.5	2950	Equivalent
D	0.047	21.0	142.0	2950	Equivalent
E	0.054	21.3	174.5	2950	Superior
F	0.051	21.6	168.0	2950	Superior
G	0.052	21.7	119.0	2950	Inferior
H	0.051	21.2	120.0	2950	Superior
I	0.050	20.6	123.0	2950	Inferior
J	0.048	19.8	128.0	2950	Inferior

* 1½ gram sample

of the resin to Whitehead Brothers' D Special sand. The screen analysis of the sand was AFS fineness No. 73. The molds were fastened with bolts and nuts and were backed up with roofing gravel. All molds were poured with a low carbon (1020) steel.

Ten lump or powdered resins were evaluated at M.I.T. A summary of the test data and a relative evaluation of the castings produced from shell molds bonded with the various resins is given in Table 1. All castings produced had varying degrees of defects. It is noted that castings produced from shell molds bonded with Resins E, F and G had less defects than the castings produced from shell molds bonded with the standard Resin A. Castings produced in shell molds bonded with Resins G, I or J had more extensive defects than were observed in the standard casting.

Of the ten powdered resins tested, Resin E was the best. Figures 3 and 4 are photographs of castings produced from shell molds bonded with Resins A and E respectively. It is obvious that the casting in Figure 4 is superior to the casting made in shells bonded with the standard resin.

Resin Coated Sands . . . One of the advantages of using resin coated sand rather than the conventional mixture of powdered resin and sand is resin economy. Since Resin E seemed most promising, sands were coated with 4 percent of this resin. Considerable difficulty was experienced in producing shell molds, which persisted in "drop-off's". Molds suitable for pouring were produced, but some building up of defective areas was necessary. The shells were much weaker than those made with any of the dry mixture of sand and resins previously tested. Casting defects were more extensive than defects shown in Figures 3 or 4.

Excellent molds were made with a coated sand prepared by Monsanto using 3½ percent of a liquid resin (K). The sand coated was Whitehead D Special. The shells were surprisingly strong for such a low resin content but castings produced in these molds were not as good as those produced in molds made of sand coated with Resin E.

Two additional types of coated sands were tested. One was a Whitehead D Special with 3.5 percent liquid of resin (K Modified) and one a mixture of Juniata and Ledington sands with 3.5 percent of resin K. Good molds were made with both coated sands, although some difficulties were experienced with "drop-off".

The casting results did not indicate anything was substantially gained by the modification brought into the resin (K) or by using Juniata and Ledington sands. It was also noted that coated sands promote cracking of the shell molds at pouring. A photograph of a typical casting produced in a shell mold made of pre-coated resin sand is shown in Figure 5.

Figure 3—Casting produced from standard shell mold, Resin A.

Figure 4—Casting produced from Resin E bonded shell mold.

Figure 5—Casting produced from shell molds made with a pre-coated resin sand.

Conclusions

1. The phenol-formaldehyde resins seem to be the only ones suitable for producing low carbon steel castings in shell molds.

2. Resins which break down slowly during the critical period when the casting skin is forming and then evolve the remaining gas evenly were most promising (see Figure 1—Resin E).

3. Shell molds can be made with less resins when pre-coated sands are used than when powdered resins are added to sand. Thus, resin coated sands contain a lesser amount of gas producing substances in the shell molds.

4. Water borne resins used in hot coating silica foundry sand proved to be the best of the coated sands for making shell molds. However, casting results showed no significant improvement.

5. Venting of shell molds helps if pyrolysis products are closing off the regular vent pores inherent in shell molds.

6. Endothermic additives to the shell molding sand assist in setting up casting skin formation before resin pyrolysis products evolve.

ABSTRACTS OF FUNDAMENTAL PAPERS ON STEEL CASTING RESEARCH

Based on a review of the current literature on technical research subjects. (Copies of these articles available from original publishers only)

Welding — High Alloy

DeLong, W. T., "A Modified Phase Diagram for Stainless Steel Weld Metals", METAL PROGRESS, February 1960. A revised diagram for predicting the amount of ferrite in stainless steel welds is proposed. It accounts for the austenitizing effect of nitrogen in the welding rod. Predictions are closer to true ferrite content than was possible with the original Schaeffler diagram.

Sands — Properties

Williams, Douglas C., "Selected Principles of Soil Mechanics Related to Sand Testing, Molds and Cores", MODERN CASTINGS, March 1960. An attempt is made to relate certain principles of soil mechanics to evaluating sand test data. According to these principles, if the compression and tensile strengths are known there can be only one value for the shear strength. A new approach to studying the subject of sand flowability is suggested.

Shell Molding

F. D. Obolentsev, "Salt Patterns for Shell Moulding," (Litie Povishenoi Tochnosti Sbornik (Symposium on Precision Casting), 1958, 43. In Russian. Abstracted in *Digest of Soviet Technology*, 1959, (5) Aug., 31. Report on Russian experiments using either zince or sodium nitride for the pattern of the shell mold. The latter material can be easily and accurately cast at 380 degrees C, it is stated, and the resulting pattern has a tensile strength of 46 kg/cm^2. After the shell mold has been made and cured at 200 degrees C, the pattern is dissolved by inserting the finished mold in warm water. A sand-bakelite mixture was used for the shell mold; dry sand is said to be a satisfactory parting agent.

Foundry Practice

Spaite, Paul W., Stephan, David G., and Rose, Andrew H., Jr. "High Temperature Fabric Filtration of Industrial Gases," U. S. DEPARTMENT OF HEALTH, EDUCATION, & WELFARE, Cincinnati 26, Ohio. Glass fiber material remains today the only commercially available fabric in general use for high temperature gas filtration. The present paper attempts to assess the field of industrial filtration over 300 degrees F in a general way, but historically it tends to be dominated by considerations related to fiber glass. Other high temperature media (asbestos, fluorocarbons, silica, aluminum silicate, etc.) are not discussed because they do not appear to offer as great a potential for widespread industrial use in the immediate future.

Corrosion Research

Nelson, E. E., "Electrode Reactions Associated with the Galvanic Corrosion of Steel", A.S.N.E. JOURNAL, February 1960. The author proposes that "antoreduction" is the process that causes corrosion and that interference with this process may produce pitting. The relation of the equilibrium potential to corrosion is discussed. A polarization diagram is given which seems to fit the corrosion of iron in neutral and alkaline water.

Corrosion Research

LaQue, Francis L., "Corrosion, an Enigma," INDUSTRIAL RESEARCH, April-May 1960. A survey of the major factors governing corrosion and corrosion control is preseted. Corrosion is difficult to predict with precision principally because the corrosion resistance of a material cannot be defined without reference to its environment. Experience and engineering approximations are necessary for a control program.

Corrosion Research

Moore, Thomas J., "Time-Temperature Parameters Affecting Corrosion of 18Cr-8Ni Weld Metals," WELDING RESEARCH SUPPLEMENT, May 1960. Boiling nitric acid corrosion tests were conducted on 0.026, 0.036, 0.047 and 0.067 percent carbon 18Cr-8Ni weld metals which were deposited using covered electrodes. All weld-metal specimens were aged at 800 to 1300 degrees F for 0.1 to 10,000 hr. prior to corrosion testing. It was found that the time-temperature-corrosion rate relationship follows a definite pattern which can be presented in the form of a three-dimensional drawing.

Non-Destructive Testing

Zandman, F., "Photoelastic-Coating Technique for Determining Stress Distribution in Welded Structures," WELDING RESEARCH SUPPLEMENT, May 1960. The basic principles and several test procedures of the photoelastic coating technique are presented. Several applications are described to indicate the use of the photoelastic-coating technique in welded structures.

Heat Treatment

"Thermocatalytic Combustion: Heat Without Flame," INDUSTRIAL RESEARCH, April-May 1960. The discussion presents a development called "thermocatalytic combustion," Within the year new products built around this development will begin to appear on the market. In the near future, thermocatalytic devices will take the form of: Engine preheaters, steam-powered tools, drying kilns, immersion heaters, pipeline heaters, wire and strip annealing furnaces, chemical processing equipment, heat-treating furnaces for metals and ceramics, high temperature hand torches, and petroleum cracking reactors.

Properties and Testing

Hull, F. C., "Cast-Pin Tear Test for Susceptibility to Hot Cracking", WELDING RESEARCH SUPPLEMENT, April 1959. A new test has been developed to evaluate the susceptibility of alloys to hot cracking, such as might occur during freezing of a weld bead or solidification of a casting. The test is quick and inexpensive, and is applicable both to the evaluation of existing materials and to studies of the effects of alloying additions and impurities on hot cracking.

Properties and Testing

Caplan, F., "Nomogram Speeds Calculation of Thermal Stresses," MACHINE DESIGN, March 31, 1960. When the temperature of a member with fixed ends is changed, stresses are set up in the member. These stresses, either tensile or compressive, are independent of the member length and can be given by an equation. The nomogram presented here gives a graphical solution of this equation.

Properties

Fleischmann, W. L., "How Irradiation Affects Metals," THE IRON AGE, April 28, 1960. Designers must consider the effects of the unique power source, nuclear fission, upon the life and reliability of equipment. Fission products, such as fast neutrons, penetrate metals and upset the orderly arrangement of atoms. Result: altered mechanical properties. How are the properties affected? To what degree? Do all metals respond equally to irradiation? To answer these and other questions, a survey of the data was recently completed and is reported.

High Alloy

"A Boron Stainless Steel with Better Toughness, Corrosion Resistance," MATERIALS IN DESIGN ENGINEERING, April 1960. High neutron absorption and excellent mechanical properties are combined in a new type 304-base stainless steel containing up to 2 percent boron-10 isotope. The new alloy, available from Carpenter Steel Co., Reading, Pa., is an improvement over type 304 containing natural boron, and will be useful for control rods, burnable poison and shielding for nuclear reactors. It offers improved design flexibility and at the same time promises to increase safety and reduce maintenance costs of nuclear power plants.

Solidification

Pronov, A. P., "Causes of Formation of Different Types of Primary Structure in Steel During Crystallization," IZVESTIYA AKADEMII NAUK SSSR, OTN, No. 4, 1951, pp. 576-8. Henry Brutcher, Technical Translations, No. 2751, P. O. Box 157, Altadena, California. Author's classification of factors governing the crystallization of a 0.30 percent carbon steel. Primary factors: Heat content of metal; properties depending on composition; deoxidizing practice, etc. Secondary factors: Cooling of casting in mold; inclusions as centers of crystallization. Experimental study of way in which ingot structure is affected by heat content of metal.

Solidification

Tageev, V. M., "Causes and Mechanism of Chemical Inhomogeneity of Alloys During Crystallization," DOKLADY AKAHEMII NAUK SSSR, Vol. 67, No. 3, 1949, pp. 491-494. Henry Brutcher, Technical Translation, No. 2732, P. O Box 157, Altadena, California. Chemical heterogeneity of ingots and castings as accounted for by the concepts of steel being a true solution of elements in liquid iron (selective crystallization) as against liquid steel being a dispersed system (movement of elements under influence of density differences). Materials studied: 1 percent carbon steel and 0.04 percent C iron. Results of experiments: Numerical data on diffusion of carbon, sulfur, and phosphorus.